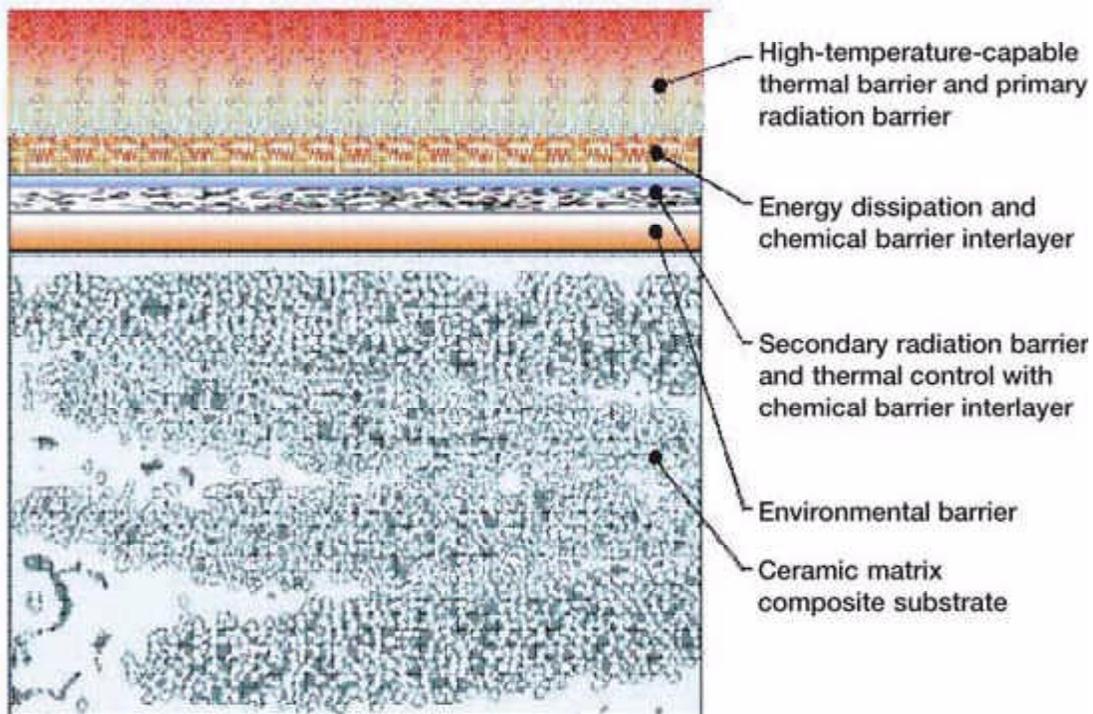


# Hafnia-Based Materials Developed for Advanced Thermal/Environmental Barrier Coating Applications

Thermal and environmental barrier coatings (T/EBCs) will play a crucial role in advanced gas turbine engine systems because of their ability to significantly increase engine operating temperatures and reduce cooling requirements, and thus help achieve engine goals of low emissions and high efficiency. Under the NASA Ultra-Efficient Engine Technology (UEET) Project, advanced T/EBCs are being developed for low-emission SiC/SiC ceramic matrix composite (CMC) combustor applications by extending the CMC liner and vane temperature capability to 1650 °C (3000 °F) in oxidizing and water-vapor-containing combustion environments. The coating system is required to have increased phase stability, lower lattice and radiation thermal conductivity, and improved sintering and thermal stress resistance under high-heat-flux and thermal-cycling engine conditions. Advanced heat-flux testing approaches (refs. 1 to 4) have been established at the NASA Glenn Research Center for 1650 °C coating developments. The simulated combustion water-vapor environment is also being incorporated into the heat-flux test capabilities (ref. 3).

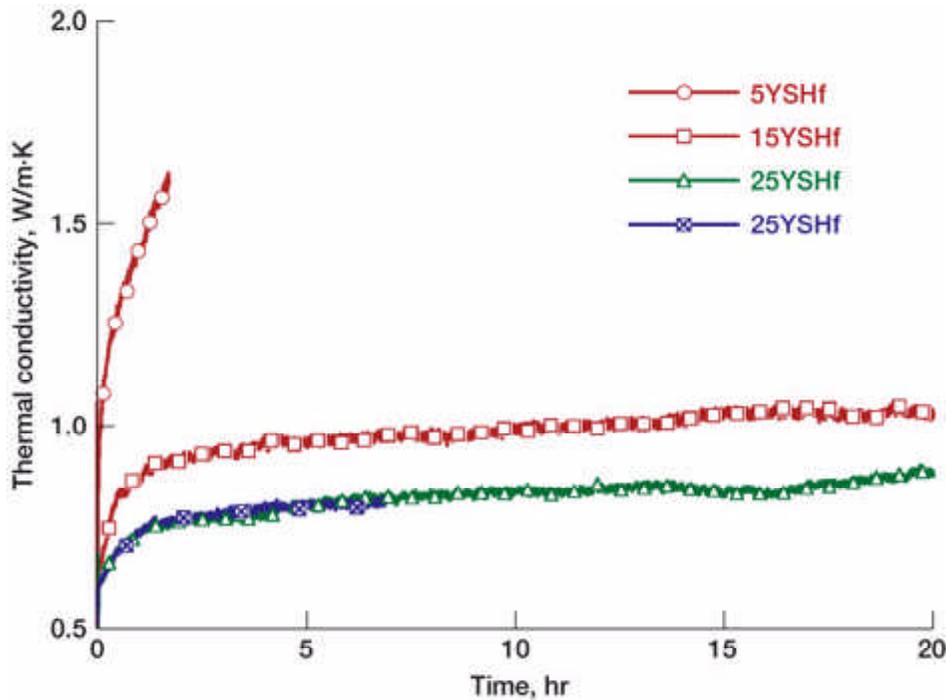


*An advanced coating design concept for the 1650 °C T/EBC system for ceramic matrix composite combustor applications.*

There are four layers on the ceramic matrix composite substrate. From top to bottom, they are (1) a high-temperature-capable thermal barrier and primary radiation layer, (2) an

energy dissipation and chemical barrier interlayer, (3) a secondary radiation barrier and thermal control with chemical barrier interlayer, and (4) an environmental barrier.

An advanced coating concept for the 1650 °C T/EBC system for CMC combustor applications is shown in the preceding schematic (ref. 5). The top layer is a high-temperature-capable thermal barrier coating, designed to provide the major thermal protection for the subcoating systems and the CMC substrate, and also to act as the first-stage radiation barrier by reducing the transmission of the infrared thermal radiations from the combustion gas environment and the higher temperature coating surface. In addition, the energy dissipation, secondary radiation barrier, and environmental barrier layers also will be incorporated to provide strain tolerance, further reduce radiation energy penetration, and ensure environmental protection. The HfO<sub>2</sub>-based oxides are being developed as potential candidate 1650 °C coating materials for advanced thermal/environmental barrier top coating applications.

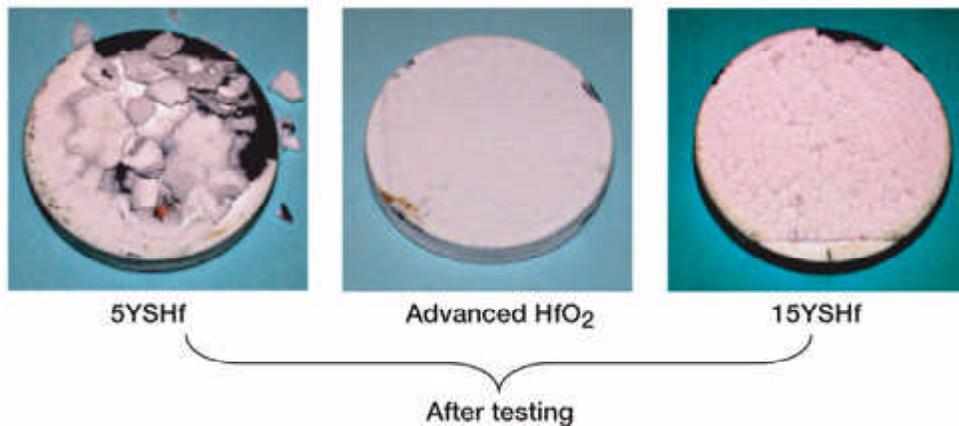
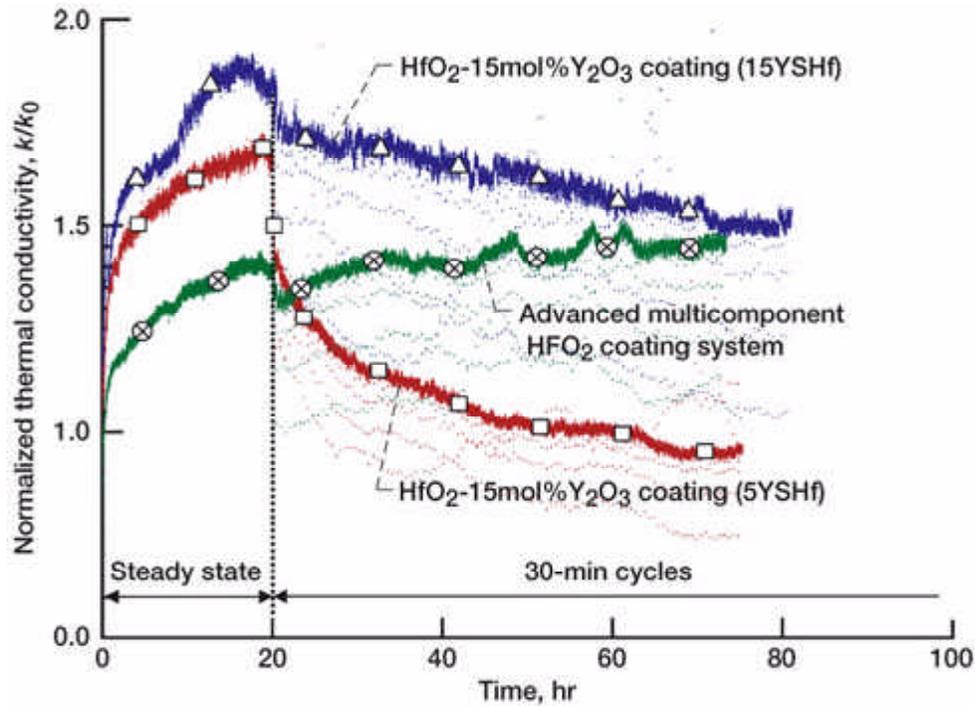


*Thermal conductivity of plasma-sprayed HfO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> coatings tested at 1650 °C as a function of time (test pass-through heat flux (95 to 100 W/cm<sup>2</sup>))*

The preceding graph shows the thermal conductivity change kinetics of plasma-sprayed HfO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> coatings as a function of time tested at 1650 °C. It can be seen that the conductivity of HfO<sub>2</sub>-5mol% Y<sub>2</sub>O<sub>3</sub> (5YSHf) increased significantly upon 1650 °C thermal exposure. On the other hand, the HfO<sub>2</sub>-15mol% Y<sub>2</sub>O<sub>3</sub> (15YSHf) and HfO<sub>2</sub>-25mol% Y<sub>2</sub>O<sub>3</sub> (25YSHf) coatings showed lower initial and 20-hr sintered thermal conductivity, indicating better temperature stability. The x-ray diffraction results showed that the as-sprayed 5YSHf initially had a partially stabilized tetragonal phase structure with a small amount of the monoclinic phase (2 to 3 mol%), and the as-sprayed 15YSHf and 25YSHf had a fully stabilized cubic structure. The monoclinic phase content in the 5YSHf increased to 12 mol% after the testing, indicating the substantial destabilization of the low-

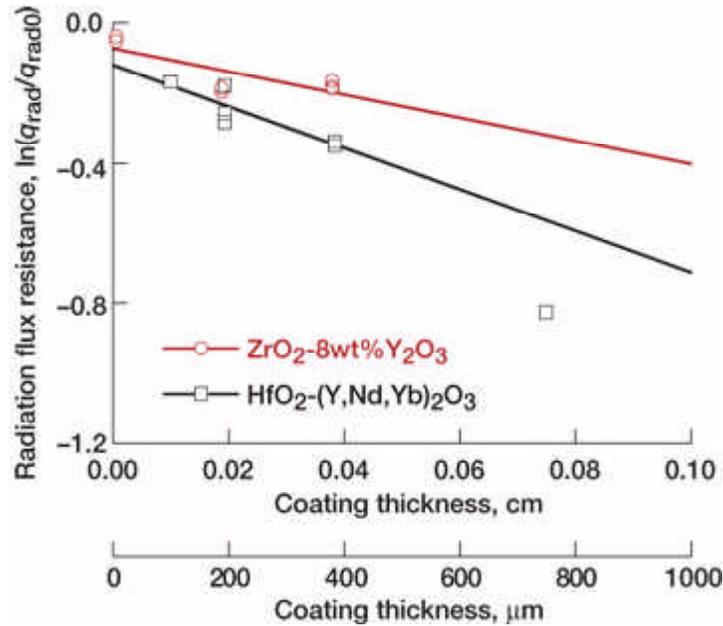
yttria-dopant coating system. Thermal conductivity generally decreased with an increase in  $Y_2O_3$  dopant. The more stable cubic-structured 15YSHf and 25YSHf showed lower conductivity and less conductivity increases in comparison to the tetragonal 5YSHf. Advanced multicomponent rare-earth-doped  $HfO_2$ - $Y_2O_3$ - $Gd_2O_3$  ( $Nd_2O_3$ )- $Yb_2O_3$  coatings have achieved even lower thermal conductivity and better thermal stability (ref. 5).

The following figure shows the 1650 °C sintering and cyclic behavior of a multicomponent  $HfO_2$ - $Y_2O_3$ - $Gd_2O_3$ - $Yb_2O_3$  coating that was coated on the mullite-based EBC/Si on SiC substrates. The advanced multicomponent  $HfO_2$  coating had a relatively low conductivity increase during the first 20 hr of steady-state testing. It also showed essentially no cracking and delamination during subsequent testing for one-hundred 30-min cycles at 1650 °C, indicating excellent sintering resistance and cyclic durability. In contrast, the  $HfO_2$  baseline coatings showed significant conductivity increases during the initial 20-hr steady-state sintering test, and later conductivity reductions because the coating had cracked and delaminated. The 5YSHf showed severe spallation partially because of the large amount of monoclinic phase formation (>25 mol%) and the phase destabilization (ref. 3).



*The 1650 °C sintering and cyclic behavior of a multicomponent  $HfO_2$ - $Y_2O_3$ - $Gd_2O_3$ - $Yb_2O_3$  coating on mullite-based EBC/Si on SiC substrates in comparison to the baseline 5YSHf and 15YSHf coatings.*

The final graph shows the radiation flux resistance  $\ln(q_{rad}/q_{rad0})$ , defined as the ratio of the pass-through radiation heat flux  $q_{rad}$  to the imposed radiation flux  $q_{rad0}$ , of a plasma-sprayed  $HfO_2$ - $Y_2O_3$ - $Nd_2O_3$ - $Yb_2O_3$  coating as a function of coating thickness, as determined by a laser-activated emitting-source flux technique. It can be seen that, in comparison to the baseline plasma-sprayed  $ZrO_2$ -8wt%  $Y_2O_3$  coating, the advanced  $HfO_2$ - $Y_2O_3$ - $Nd_2O_3$ - $Yb_2O_3$  coating improved radiation resistance significantly. The advanced high-stability, low-conductivity 1650 °C  $HfO_2$  coatings will affect NASA's UEET low-emission combustor technology significantly.



*Significantly improved radiation resistance is demonstrated for an advanced plasma-sprayed HfO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub>-Nd<sub>2</sub>O<sub>3</sub>-Yb<sub>2</sub>O<sub>3</sub> coating in comparison to a baseline plasma-sprayed ZrO<sub>2</sub>-8wt%Y<sub>2</sub>O<sub>3</sub> coating.*

## References

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**Programs/Projects:** UEET (Advanced 3000 °F coatings concepts)